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Research and development of natural-gas fueled engines in Iran

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ABSTRACT

As global energy demand rises, natural gas (NG) plays a pivotal role in energy supply. Natural gas is the cleanest fossil fuel and it has high energy conversion efficiencies for power generation. Natural gas has been extensively investigated for use in spark-ignition (SI) and compression-ignition (CI) engines. This paper consists of two sections: the first section gives an overview of natural gas fuel in the world and highlights the share of natural gas in Iran energy market and then expounds the role of natural gas vehicles (NGVs) in the context of Iran environmental pollution and its sustainable development. It is concluded that natural gas is the promising alternative fuel for vehicles in Iran. In the second part, the paper reviews the research works on natural gas fueled engines by Iranian researchers, and reports the most achievements obtained by them in the field of the natural gas fueled engines which involve natural gas-fueled SI engines, dual fuel (natural gas/diesel) engines, and Homogenous Charge Combustion Ignition (HCCI) engines. It is found that Iranian researchers started investigations on NGVs along with world researchers and developed research in line with their needs and priorities. Recently they further focused on this topic and their contribution to this field is significant especially regarding dual fuel engines.

Contents

1. Introduction

Global warming and energy crisis are among the most important issues that threaten the peaceful existence of the mankind. Their adverse effects have been much more obvious during the past century and no certain solution is introduced to confine their deleterious effects on the planet. There are three major forms of fossil fuels: coal, oil and natural gas (NG). During the nineteenth and early twentieth century coal was the only used fuel but was gradually replaced by oil right after World War II. The application of natural gas in the world goes back to the middle of twentieth century when, the share of natural gas has been progressively increased within the energy market. These three fossil fuels account for more than 85% of the world's primary energy as shown in Fig. 1 [1]. The consumption of fossil fuel is continuously rising due to the population growth as well as development of industries and transportation facilities. The world's total energy consumption has increased by about 38% over the last decade. In addition, global energy consumption grew by 2.5% in 2011 compared with 2010. These energy trends can be seen in Fig. 2.

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Increased energy demand requires increased fuel production, draining current fossil fuel reserve levels at a faster rate [2]. Fig. 3 depicts the world primary energy demand by fuel from 1980 to 2035 years. It is clear that gas overtakes coal before 2030 and meets one quarter of global energy demand by 2035. In addition, through 2030, gas demand grows by 2% per year, compared with just 1.2% per year for total energy [3]. According to the International Energy Outlook 2013 natural gas is the fastest-growing primary energy source in the future. Natural gas consumption is forecasted to be double between 2020 and 2040, with the most robust growth in demand expected among the developing nations [4].

Increasing fossil fuel prices and their deterioration to environment have led to the search for alternative fuels since past several decades. Natural gas is one of such fuels available in large quantities in many parts of world at attractive prices. Natural gas is expected to be the promising fuel for many countries in the future because it is a cleaner fuel than oil or coal and not as controversial as nuclear power. Natural gas combustion is clean and emits less CO_2 compared to other fossil fuels, which makes it favorable for utilization in internal combustion engines (ICEs). Natural gas is used across all sectors including in industrial, residential, electricity generation, commercial, and transportation sectors. Natural gas vehicles (NGVs) are widely used in the Asia-Pacific region (especially Iran), Latin America, Europe, and North America due to increase in gasoline prices.

It was found that exhaust emissions of NGVs are much lower compared with gasoline or diesel engines. Natural gas can be stored in compressed form known as compressed natural gas (CNG), or at a low temperature (111 K) in liquid form, known as liquefied natural gas (LNG). It is unfeasible to use natural gas as a transportation fuel at ambient temperatures and pressures. Therefore, it must be either compressed or liquefied to increase its volumetric energy density [5].

The gigantic issues on energy depletion and environment deterioration brought by the vehicle industry are more remarkable in Iran, and they already have been the obstacles of the sustainable development of Iran. Since the mid of 1990s, Iranian vehicle industry has been developed greatly, and the continuous increase of vehicles led to the increases need for more petroleum. Meanwhile, the massive air emissions emitted from the vehicles are deteriorating Iran environment and changing the climate. For solving the urgent issues, searching environmental benign, plenteous supply, cost effective and reliable fuel for vehicles and utilizing the fuel in vehicles have become one utmost urgent task for Iran government. Among many and various alternative fuels, natural gas is the fuel which can satisfy the requirements well. As will be mentioned later, Iran has very rich fossil energy resources. Iran has the world's second largest reserves of natural gas and is one of the leading countries in utilization of natural gas in internal

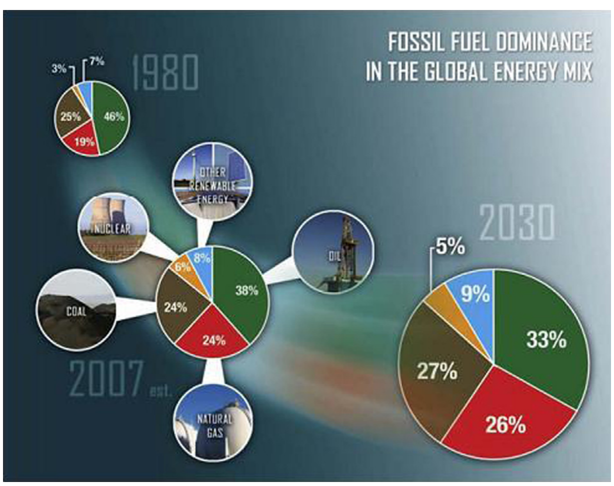


Fig. 1. The share of World energy, past, present and future [1].

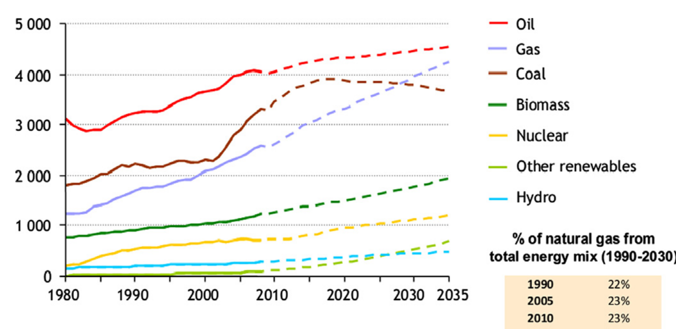


Fig. 3. World primary energy demand by fuel [3].

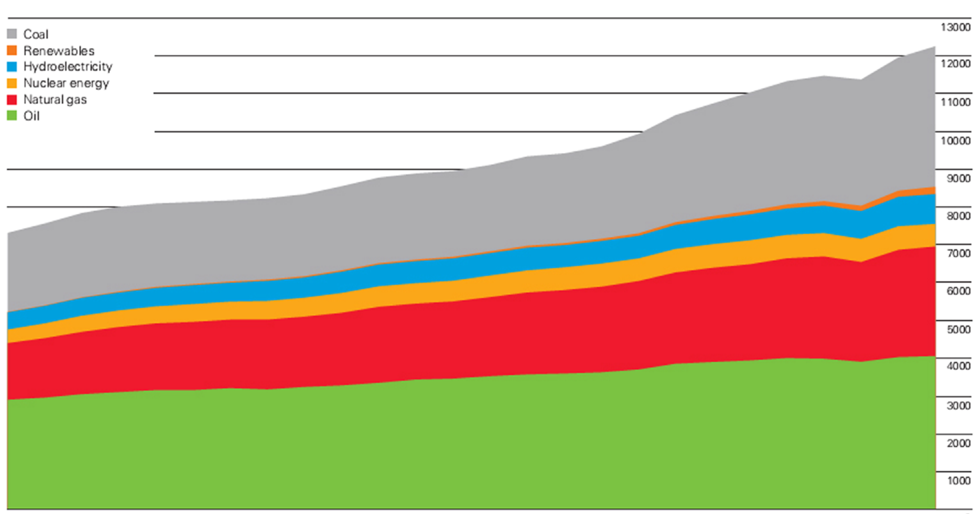


Fig. 2. Fossil fuel consumption from 1986 to 2011 with approximate current reserves-to-production ratios in remaining years [2].

combustion engines. CNG projects in Iran were started in 1975 with the conversion of 1200 taxis and private passenger cars in Shiraz city as a pilot project. Since that time, CNG vehicles have achieved an appreciable share in the vehicle stock of Iran [6].

There have been some previous reviews regarding the natural gas application in internal combustion engines; however none of them extensively discussed and analyzed natural gas fuel and its application in internal combustion engines in Iran [7–11]. Due to the distinguished characteristics of natural gas, abundance of natural gas fuel and NGVs in Iran, investigating the performance and emissions characteristics of natural gas fueled engines become one of the utmost important research directions for Iranian researchers. The present paper reviews the background, prospects and challenges of natural gas fuel and natural gas fueled vehicles in Iran along with progress of the research works on natural gas fueled engines in Iran, and reports most of the achievements obtained by Iranian researchers during the process in order to make them known to the world. In the first part of the paper, the role of natural gas fuel in the world and Iran energy market as an alternative fuel for NGVs is discussed and then a summary of research works on natural gas implication in SI, CI, dual fuel and HCCI engines in Iran is presented. The results of this study provide a comprehensive insight for future researchers in Iran to address the oncoming research challenges regarding natural gas fueled ICEs.

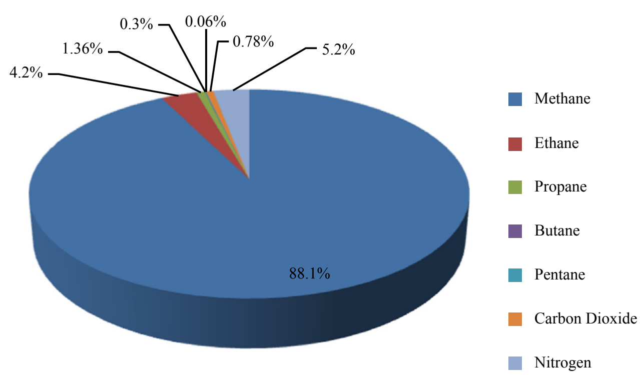


Fig. 4. Typical natural gas composition by volume.

Table 1
Properties of natural gas, gasoline and diesel fuels [13].

Property	Gasoline	No. 2 diesel	CNG
Chemical formula	C_4 to C_{12}	C_3 to C_{25}	CH_4
Molecular weight	100–105	≈200	16.04
Carbon	85–88	84–87	75
Hydrogen	12–15	33–16	25
Specific gravity	0.72–0.78	0.81–0.89	0.424
Energy per kilogram (MJ/kg)	46.4	45.4	53.6
Boiling temperature, °C	26–225	188–344	−31.7
Freezing point, °C	−40	−40–35	−182
Flash point, °C	−45	72	−184
Autoignition temperature, °C	246–280	210	540
Flammable range (%)	1–7.6	0.6–5.5	5.3–15
octane number	87	30	125
cetane number	5–20	40–55	–
Specific Heat, J/kg/K	2008	1800	–

2. Natural gas as a vehicular fuel

Natural gas is a hydrocarbon gas mixture consisting primarily of methane, with other hydrocarbons, carbon dioxide, nitrogen and hydrogen sulfide. A detailed typical composition of natural gas in Iran is given in Fig. 4 [12]. Table 1 lists the properties of natural gas, gasoline and diesel fuels [13]. Typical combustion properties of natural gas are given in Table 2 [14].

A natural gas vehicle is an alternative fuel vehicle that utilizes CNG or LNG as an environmentally friendly alternative fuel instead of fossil fuels. Exhaust emissions from NGVs are much lower compared to equivalent gasoline-powered vehicles. In addition, less carbon dioxide is produced by combustion of natural gas than by combustion of both diesel fuel and gasoline, which makes natural gas engines favorable in terms of the greenhouse effect. NGVs also emit very low levels of carbon monoxide (approximately 70% lower than a comparable gasoline-powered vehicle) and volatile organic compounds. They have considerable effect on breaking down methane and some other greenhouse gases in the atmosphere, and thus increase the global rate of methane decomposition. Regarding environmental performance, LNG is a poor fuel compared to CNG, because it requires energy to be liquefied and to be transported, however, LNG is still superior to alternatives such as fuel oil or coal in most cases [14].

NGVs running on CNG are appropriate cases for high-mileage, centrally-fueled fleets that operate within a limited area. LNG is a good choice for vehicles needing to travel long distances [15]. There are three types of NGVs:

- Dedicated: These vehicles are designed to run only on natural gas.
- Bi-fuel: These vehicles have two separate fueling systems that enable them to run on either natural gas or gasoline.
- Dual-fuel: These vehicles are traditionally limited to heavy-duty applications, have fuel systems that run on natural gas, and use diesel fuel for ignition assistance.

Light-duty vehicles typically operate in dedicated or bi-fuel modes, and heavy-duty vehicles operate in dedicated or dual-fuel modes. Generally, dedicated NGVs show better performance and lower emissions compared to bi-fuel vehicles. Dedicated NGVs produce little or no evaporative emissions during fueling and use. For gasoline vehicles, evaporative and fueling emissions account for at least 50% of a vehicle's total hydrocarbon emissions. Dedicated NGVs can also reduce carbon dioxide exhaust emissions by almost 20%. Because dedicated NGVs only have one fuel tank, they are not as heavy as bi-fuel NGVs. The driving range of NGVs generally is less than that of comparable conventional vehicles because of the lower energy density of natural gas. Light-duty natural gas vehicles work much like gasoline-powered vehicles with spark-ignited engines [16].

Table 2
Typical combustion properties of natural gas [14].

Ignition point	876 K
Theoretical flame temperature (stoichiometric air-to-fuel ratio)	2233 K
Maximum flame velocity	0.3 m/s
Water vapor content	16–32 mg/m^3
Sulfur content	5.5 mg/m^3
Higher heating value (dry basis)	36.0–40.2 MJ/m^3

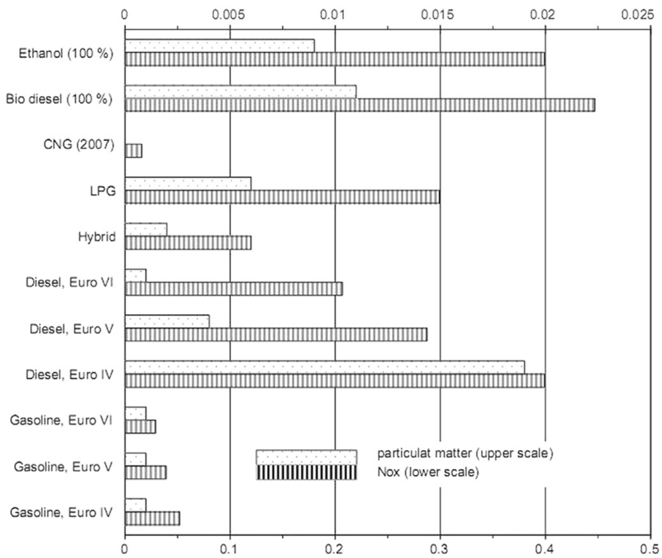


Fig. 5. Comparison emissions of NO_x and particulate matter for different fuels [9].

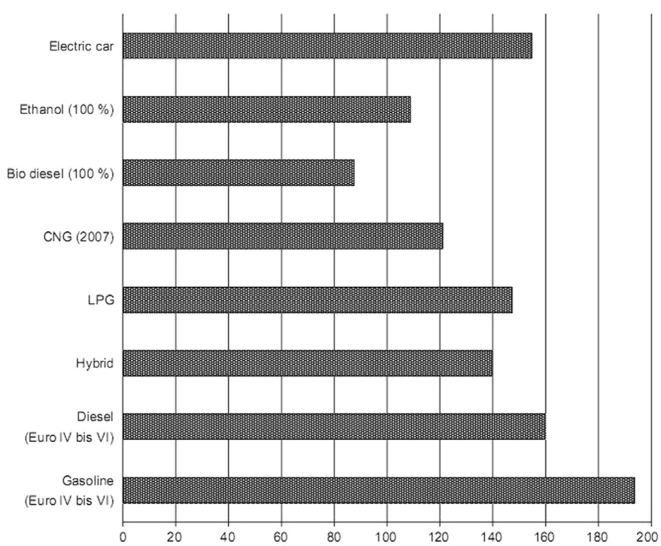


Fig. 6. Greenhouse gas emissions comparison across fuels [9].

Heavy-duty engines can also run on diesel and natural gas in a dual-fuel mode using diesel fuel as the pilot fuel and gaseous fuel as the main fuel. Dual fuel engines are one of the possible short-term solutions to reduce emissions from traditional diesel engines, meanwhile, utilizing an alternative fuel like natural gas as primary fuel. It consequently results not only in an interesting technology to meet future emissions regulations, but also a powerful solution to retrofit existing engines. There is no significant loss in power in dual-fuel operation compared to conventional CI-engine operation except at part loads [17].

2.1. Natural gas fuel advantages and disadvantages

The advantages of converting vehicles to natural gas use, or buying factory built dedicated natural gas vehicles are:

- Natural gas is readily – and abundantly – available now from stable sources that offer security of supply. It is a domestic fuel; all percentage of natural gas used in Iran is produced in Iran.
- CNG is a safe fuel. It is lighter than air and disperses easily into the atmosphere and does not form a sufficiently rich mixture for combustion to take place. CNG has a high octane number, which is considerably higher than that of gasoline; consequently, CNG vehicle is more energy efficient. Higher octane number allows higher compression ratios and improved thermal efficiency, reducing carbon dioxide emissions. Catalytic converters can be used more efficiently in CNG vehicle than diesel.
- Replacing a typical older in-use vehicle with a new NGV provides significant reductions in exhaust emissions of carbon monoxide (CO) by 70–90%, non-methane organic gas (NMOG) by 50–75%, nitrogen oxides (NO_x) by 75–95% (Fig. 5) and carbon dioxide (CO_2) by 20–30% (Fig. 6). The transition to CNG vehicles could contribute to reach emissions of 130g CO_2/km on average for new cars by 2015.
- Because of gaseous state of CNG fuel, NGVs have better starting and drivability even under severe hot and cold weather conditions.
- Natural gas fuel is much cheaper than gasoline and diesel fuels in Iran.
- Natural gas show better engine wear and maintenance characteristics. Noise level of CNG engine is much lower than that of diesel. The internal parts of the engines that have run on natural gas almost remained new.
- Vehicles can be adjusted to run on both natural gas and gasoline (bi-fuel) or natural gas and diesel (dual fuel) with a switch [9,18–22].

There are also some challenges to be overcome in using natural gas as a vehicular fuel:

- The first and main issue is storage of natural gas. Nowadays natural gas is stored onboard the vehicle by CNG cylinders. These cylinders store natural gas at very high pressures, but are somewhat bulky for the amount of energy they produce. Consequently, most of converted natural gas vehicles have a limited range.
- Acceleration of dedicated NGVs is slower than performance of the same engine running on gasoline. On the other hand, engines operating on the bi-fuel mode have to be adjusted between optimal settings for either fuel and thus lose more performance in either natural gas or gasoline mode. As a result, new engine developments should be found that increase engine compression ratios to better match the octane number of natural gas, and limit or eliminate this performance problem [18,22].

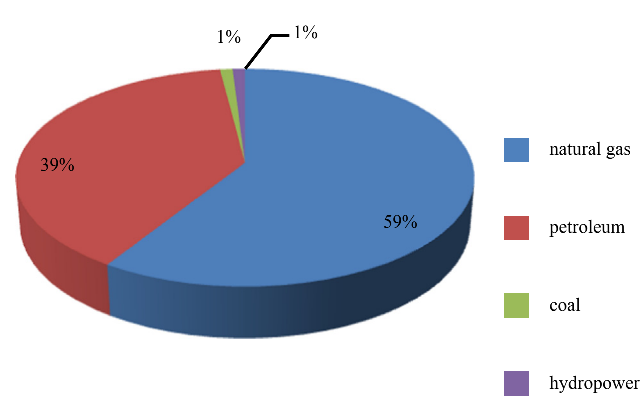


Fig. 7. Iran's total energy consumption share by fuel (2010).

3. Natural gas vehicles in Iran

Iran is located in southwest of Asia with about 1648,195 km^2 area. The population of Iran has increased from 61.83 million in 1998 to 75.14 million in 2012 [23]. Iranian energy sector is largely depends on the crude oil and natural gas and about 99% of energy production in Iran is from oil & gas (Fig. 7) [24,25]. Iran is ranked 10th among the most polluted countries and According to Fig. 8, Iran is among the top 10 GHG emitting countries in the world [26].

As mention in previous section, natural gas has many advantages such as its domestic availability, widespread distribution infrastructure, low cost, and clean-burning qualities to be used as a transportation fuel in Iran. In June 2013, Iran overtook the Russia and become the world first country with largest reserves of natural gas (17.9% of the world's total). Because of the huge investments by Iranian government, production of natural gas in Iran is expected to increase over the next few years. Iran has the third largest consumption of natural gas in the world after United States and Russia. Iran also has the world's largest growth rate in natural gas consumption [2]. As illustrated in Fig. 9, Iran has a large amount of natural gas pipelines network in all over the country, contains more than 100,000 km in 900 cities and 11000 villages. This wide network of gas pipelines gives rise to high ability and facility to feed of natural gas to the CNG station [27].

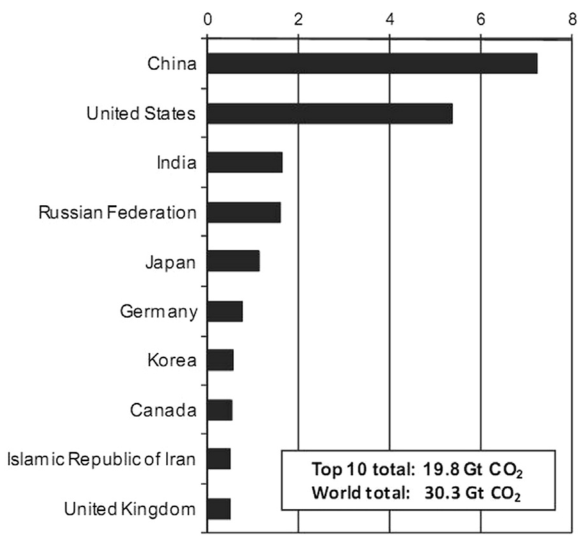


Fig. 8. The top 10 emitting countries account for nearly two-thirds of the world CO_2 emissions [26].

The history of NGV technology is old and inconsistent. In 1930, the U.S. was the first country to use NGVs. CNG projects in Iran were started in 1975 with the conversion of 1200 vehicles in Shiraz as a pilot project and two refueling stations were constructed there. After a pause, the CNG program started in Mashhad in 1985 and over 1200 NGVs and 22 refueling stations were built there. Subsequently, in 1990, The United Bus Company of Tehran & suburbs researched on conversion of buses in urban trips that were operated in 1994. A comprehensive project for creating infrastructure and developing CNG in Iran was started by Iranian Fuel Conservation Organization (IFCO) in 2001 with some separate activities in parallel, as explained below [6,28]:

– Conversion of retrofitted vehicles to CNG
– CNG vehicles manufacturing
– Legislation of national directives and regulations
– Construction of CNG refueling stations.

Currently, more than 17 million NGVs and 20,000 stations exist worldwide and NGV Global (IANGV) is projecting that this will increase at least ten-fold, to 50 million vehicles by 2020 with annual growth rate of 3.7%. As shown in Fig. 10, about half of the world natural gas vehicles and stations are in Asia Pacific. Iran is one of the fast growing countries in production of NGVs. Fig. 11 shows the NGVs growth in Iran during 1995–2012 years. It is clear that there has been a sharp increase in number of NGVs after 2007. In addition, as can be seen in Fig. 12, by the end of 2012, Iran had the world's largest fleet of NGV at 3.30 million vehicles [29]. Over the last decade Iranian government has intervened to decrease the society's dependence on gasoline in order to grow of NGV market in large parts in Iran. The implemented plan was to decrease the effect of sanctions on Iran and make the nation's domestic market

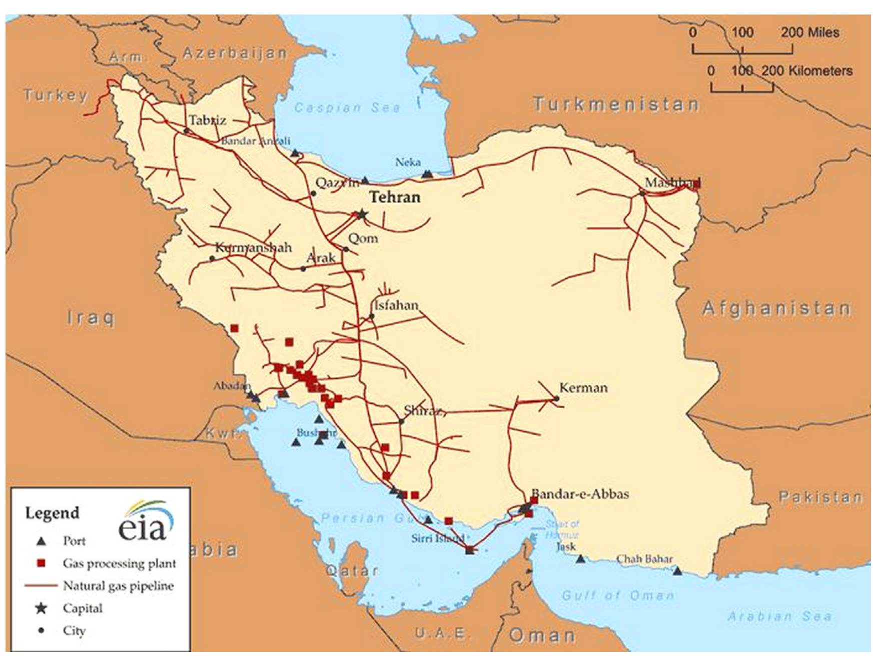


Fig. 9. Iran's natural gas pipeline infrastructure [27].

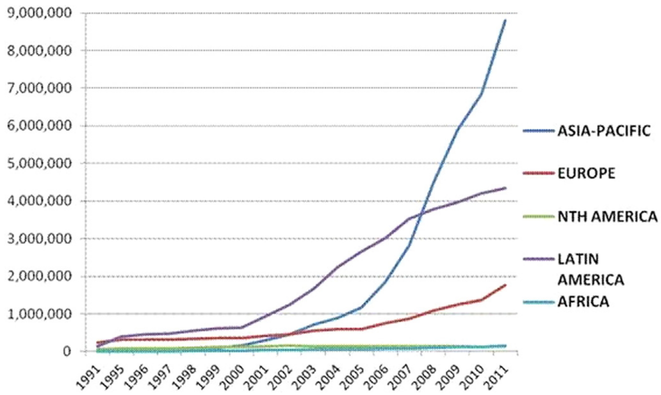


Fig. 10. Natural gas vehicles by region 1991–2011 [15].

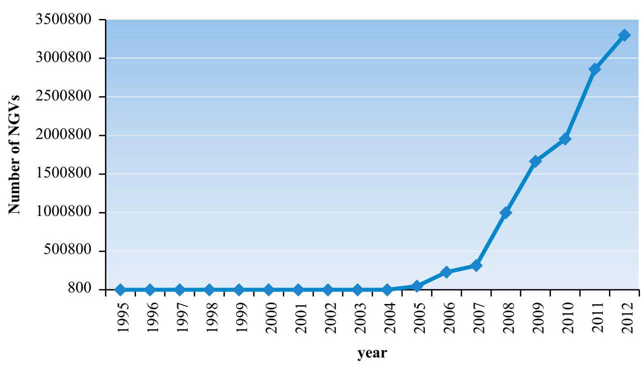


Fig. 11. NGVs growth in Iran.

less dependent on imported gasoline. The NGV's have been manufacturing through local manufacturers using bi-fuel engines. Also by 2012, 1.5 million CNG cylinders per year have been produced by Iranian manufacturers and therefore Iranian government has banned their imports to support the local manufacturers. Furthermore, CNG industry in Iran costs the least compared to the rest of the world [30–32].

Iran is one of world's fast growing countries in terms of the highest number of CNG stations. Currently, there are about 2200 CNG stations operating in Iran, but the number is expected to increase to 3000 over the few next Iranian years (Fig. 13) [15]. Since the number of CNG stations does not satisfy number of NGVs in Iran, so it is very important to convert them as bi-fuel engines, which can run on both gasoline and CNG fuels. The development of bi-fuel technology depends on some fields such as CNG tanks, natural gas engine control units (ECUs), catalyst converters and gas injectors. Regarding the public transportation fleet, the manufacturers have produced CNG buses and these buses have been successfully in service in recent years. Dual fuel engines are the second choice instead of diesel engines. As an example OM355 engine (which is the diesel engine of many buses in Iran) was converted to dual fuel engine and tested successfully. Converting gasoline engine of taxies to bi-fuel engines is another phase of public transportation fleet project. There are some reasons that prevent to develop natural gas dedicated engines technology in Iran. One of them is the economic and technological impossibilities to manufacture a huge amount of natural gas dedicated engines in a short term program. The other one is lack of fuel stations, especially in highways. So the process of producing NG dedicated engines is not a primary solution. Some powertrain research and development centers in Iran, like IPCO (Irankhodro Powertrain Co.), have projects to design and produce dedicated natural gas engines. But Results of these programs would be used in the future. According to the NGV master plan, by the year of 2020, 46 to 70% of the total vehicles in Iran must be NGVs and 2950 to 4500 fuel stations must have been constructed [6].

One of the first studies in Iran about conversion of conventional vehicles to operate by NG was performed by Ebtekar [33]. He reported that the conversion of vehicles to operate by LPG and CNG fuels could be more economically and environmentally friendly option in Iran. He also stated that Iran could become a leader in the development of gaseous fuel powered vehicles in the future while containing its major source of air pollution.

4. Natural gas in spark-ignition engines

The earliest research on bi-fuel engine in Iran should be traced back to the middle of 1990s, when natural gas was employed as the secondary fuel in gasoline engine. Subsequently, the curtain of bi-fuel engine has been opened on the stage in Iran. The research on the bi-fuel NGVs has made a breakthrough during the recent decade, as shown in Table 3.

Dordaei et al. [34] experimentally investigated the pollutant emissions of a SI engine with CNG fuel. They studied the effects of various parameters such as air-fuel ratio, the shape of combustion chamber and spark timing on pollutant emissions of the engine and they found that combustion chamber shape has a significant effect on exhaust emissions. Shariat [35] analyzed the performance of a bi-fuel spark ignition engine running both on natural gas and gasoline. He compared the results of closed-loop and open-loop gas supplying systems. The effect of ignition timing on the power loss was discussed. The power and emissions of the converted vehicle were compared with the base power and emission values for a series of engine speeds. The reasons for the power loss were explained and some useful methods were recommended to reduce the amount of power loss.

Shamekhi et al. [12,36] experimentally investigated engine performance and exhaust emissions in a SI bi-fuel engine for both natural gas and gasoline fuels in a wide range of engine operating conditions. A common rail fuel injection system was used for CNG in order to control air-fuel ratio precisely. The results showed that at all engine speeds, volumetric efficiency decreased about 10 to 14.2% and power and torque have been decreased about 10.8 to 14%. Besides, thermal efficiency of CNG fuelled engine was increased between 22 and 33%. In addition, HC, CO and CO_2 emissions were decreased and the NO_x emissions were the only ones that show an increase in their amounts.

Andalibi and Ahmadi [37] stated that the amount of charged air should be increased in NG mode of bi-fuel engine to prevent power fall. Since thermodynamic and mechanical design concepts are entirely based on gasoline mode, torque and power values are lower in natural gas mode than gasoline one. Thus, theoretically, more air should be supplied in NG mode.

Ghanbari et al. [38] proposed a refined model for analysis of engine knock when using natural gas fuel and EGR. The model was used to compare the effectiveness of EGR to other knock suppression methods such as lean-burn combustion, compression ratio reduction, and ignition timing retardation. The model was consisted of two zones: a burned combustion products region and an unburned reactants comprising the end gas region, separated by a flame front of negligible thickness. Results showed that EGR addition was more effective at suppressing knock, while maintaining high thermal efficiency and output work, compared to other knock suppression techniques such as inlet pressure and temperature, equivalence ratio, spark timing, or compression ratio.

Dashti et al. [39,40] thermodynamically simulated and evaluated a spark ignition engine to run on both gasoline and CNG. They used a two-zone model to simulate and predict the

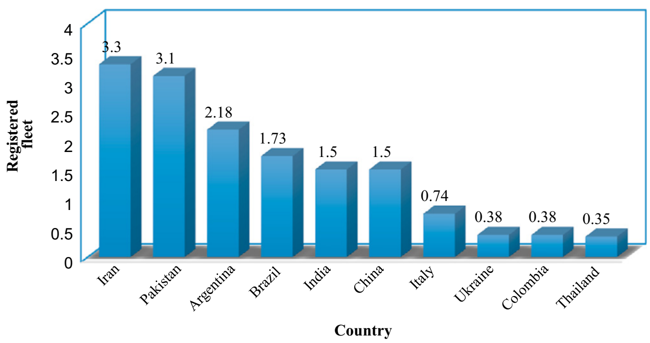


Fig. 12. Top ten countries with the largest CNG vehicle fleets (millions).

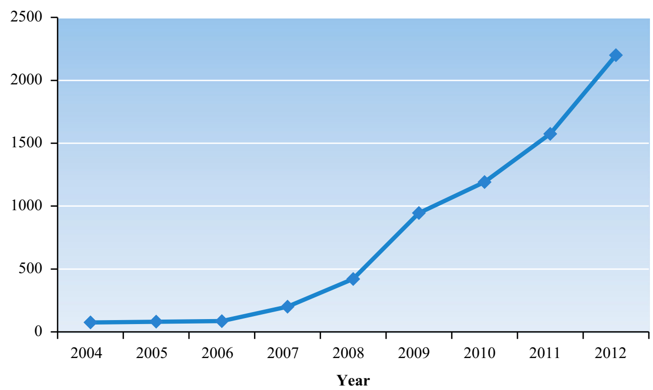


Fig. 13. Number of CNG stations in Iran between 2004 and 2012 years.

combustion process and the mass burning rate considering the propagation of the flame front spherically. Different parameters including power, IMEP, ISFC, thermal efficiency and emissions concentration of SI engine running on both gasoline and CNG fuel were determined. They further carried out parametric studies to evaluate the effects of equivalence ratio, compression ratio and spark timing in the SI engine using gasoline and CNG fuels on performance characteristics and emissions concentration in order to show the capability of the model to predict of engine operation.

Abianeh et al. [41] investigated the influence of fuels on wall temperature, performance and emissions in a bi-fuel engine which uses CNG as the primary fuel and gasoline as the secondary fuel. They indicated that the decrease in power output usually found in the CNG engine, resulting from the use of gaseous CNG fuel, was minimized by increasing the high compression ratio, adding increasing valve lift, optimizing valve timing and reducing engine backpressure. However, the power output needs to be improved further to equal that of gasoline. The CO and NMHC (Non-Methane Hydrocarbon) emissions from the engine running on natural gas were lower than those of an engine running on gasoline under similar conditions. The comprehensive obtained results are shown in Fig. 14.

Mirsalim et al. [42] performed energy and exergy analyses on a turbo charged four stroke bi-fuel CNG-gasoline engine. Based on the obtained results, the exergy efficiency was maximum at a speed of 2500 rpm and the speed in which the maximum exergy and energy occur was not the same. They found that utilizing the unused output energy of the engine can enhance useful work and therefore improve engine efficiency.

Firouzgan [43] evaluated two generations of gas fueling systems including Mixer type and Sequential system type in a bi-fuel (gasoline/CNG) engine. He measured various parameters including performance, emissions and fuel consumption of bi-fuel engine. He reported that the sequential gas fueling system is better than the mixer type. The power loss in mixer type is 1.78% higher than that of the other one. On the other hand, injection multi-point sequential gas system makes 1.75% improvement in torque view.

Rezapour et al. [44,45] modeled a four-stroke bi-fuel SI engine based on the two-zone combustion model. He measured volumetric efficiency, brake power, brake mean effective pressure, torque, brake specific fuel consumption and emissions. He expounded the comparisons on effect of engine speed, equivalence ratio and performance parameters. They reported that the CNG has advantages and disadvantages as compared with gasoline. The natural gas forms a more homogenous mixture in comparison with gasoline. It is cheaper than gasoline and produces the least rate of CO while gasoline produces more power and less NO_x compared to CNG. They also studied the exergy (availability) analysis in bi-fuel (CNG and gasoline) spark ignition engines. The engine was modeled based on a thermodynamic quasi-dimensional (QD) two-zone model. He discussed the effect of equivalence ratio, ignition time and engine of speed upon the terms of availability, the first law of thermodynamics (FLT) and the second law of thermodynamics (SLT) efficiency. The results showed that differences of operational parameters that had affected the availability transfers, irreversibilities and efficiencies. The irreversibilities had minimum values for the specified engine speed; equivalence ratio and optimal ignition time (spark advance), when the total availability in the engine cycle reached a maximum.

Behnam et al. [46] proposed a new method for modeling of bi-fuel (gasoline/LNG) SI engine using feed forward (FF) artificial neural network (ANN). The engine had three inputs including the engine speed, ignition spark timing, and air fuel ratio (AFR), and four outputs including, brake power, brake torque, brake mean effective pressure (BMEP) and brake specific fuel consumption (BSFC). The numerical results were validated with experimental data and showed that modified back propagation with classification of Points method, significantly improves the engine ordinary ANN models performance for prediction.

Ebrahimi and Mercier [47] made experimental investigation to observe the effects of natural gas fuel on the engine performance of a bi-fuel engine in comparison to gasoline fuel. They conducted experiments with the spark timing adjusted to MBT timing with wide open throttle (WOT) condition at different engine speeds and equivalence ratios for gasoline and natural gas operations. It was concluded that natural gas operation causes an increase of about 6.2% in BSFC, 22% in water temperature difference between outlet and inlet engine, 3% in exhaust valve seat temperature, 2.3% in brake thermal efficiency (BTE) and a decrease of around 20.1% in maximum brake torque (MBT), 6.8% in exhaust gas temperature and 19% in lubricating oil temperature when compared to gasoline operation (Fig. 15). The equivalence ratio of maximum MBT is higher than equivalence ratio of maximum BTE for natural gas and gasoline operations. The exhaust gas temperature of gasoline operation is higher than that of natural gas operation, while the exhaust valve seat temperature of natural gas operation is higher. The exhaust gas and the lubricating oil temperatures for gasoline operation are higher than those for natural gas operation while the exhaust valve seat temperature for natural gas operation is higher (Fig. 16).

Ebrahimi [48] further studied the effects of assumed specific heat ratio on the heat release analysis of engine pressure data in a spark ignition engine, using natural gas and gasoline fuels. The combustion parameters were obtained from the heat release rate, which its own was obtained from the first law of thermodynamics during a cycle. The results indicated that the combustion

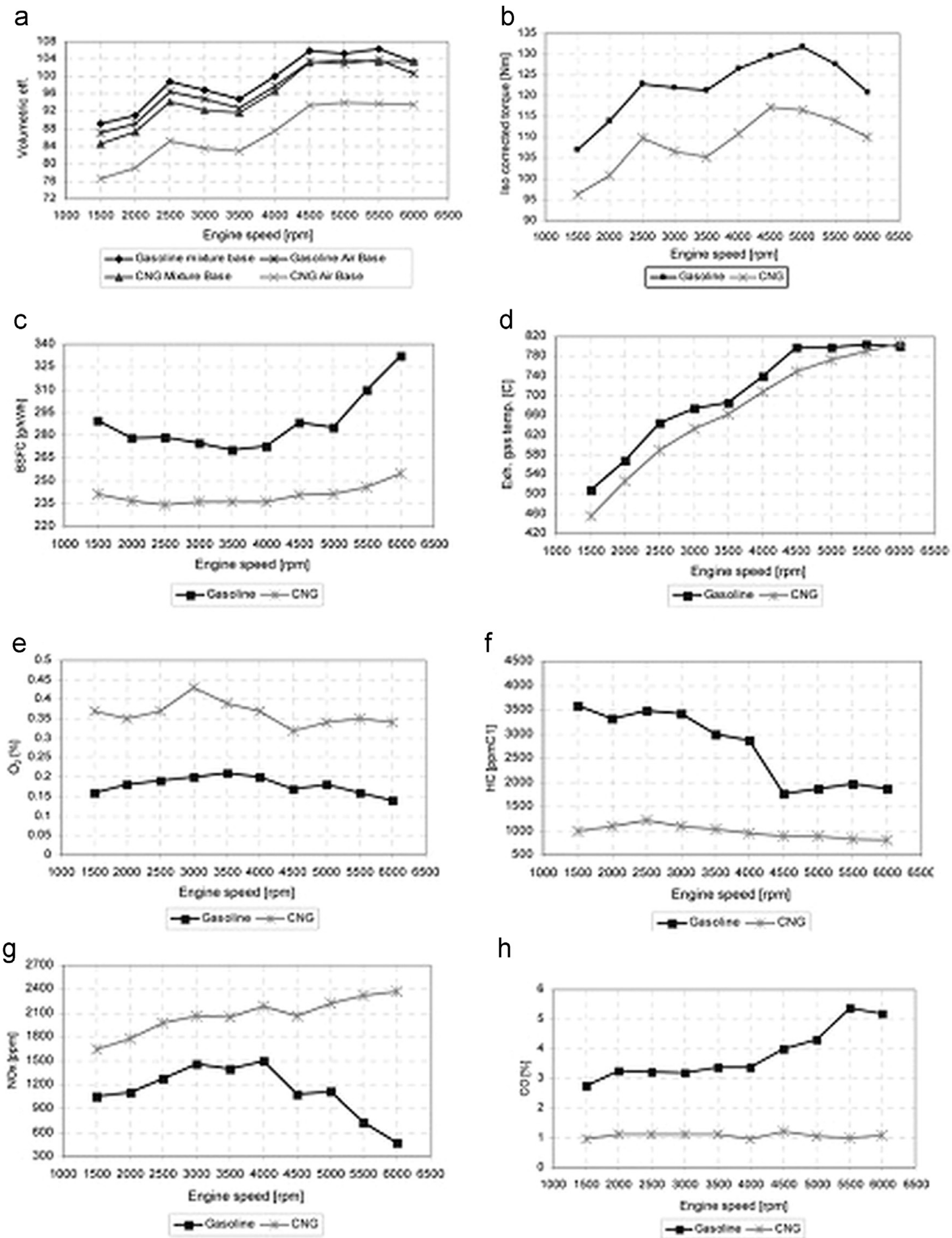


Fig. 14. Comparison of gasoline and CNG fueled engine characteristics at full load conditions: (a) volumetric efficiency; (b) corrected torque; (c) brake specific fuel consumption; (d) exhaust gas temperature; (e) O_2; (f) Total hydrocarbon emissions; (g) NO_x emissions, (h) CO emissions [41].

parameters have high sensitivity to the variation and first derivative of the specific heat ratio. The results also showed that the influence of the first derivative of the specific heat ratio on the combustion parameters for natural gas operation is higher than that for gasoline operation. Moreover, the first derivative of the specific heat ratio for determination of combustion parameters should not be ignored.

Asgari et al. [49] reported experimental and theoretical results for a spark ignition engine running on CNG as a fuel. They theoretically used a zero-dimensional, multi-zone combustion model in order to predict nitric oxide (NO) emission in a spark ignition (SI) engine. During combustion, 12 products were obtained by chemical equilibrium via Gibbs energy minimization method and nitric oxide formation was calculated from chemical kinetic by the extended Zeldovich mechanism. The superiority of the multi-zone model over its two-zone counterpart was demonstrated in view of its more realistic in-cylinder NO emissions predictions when compared to the available experimental data.

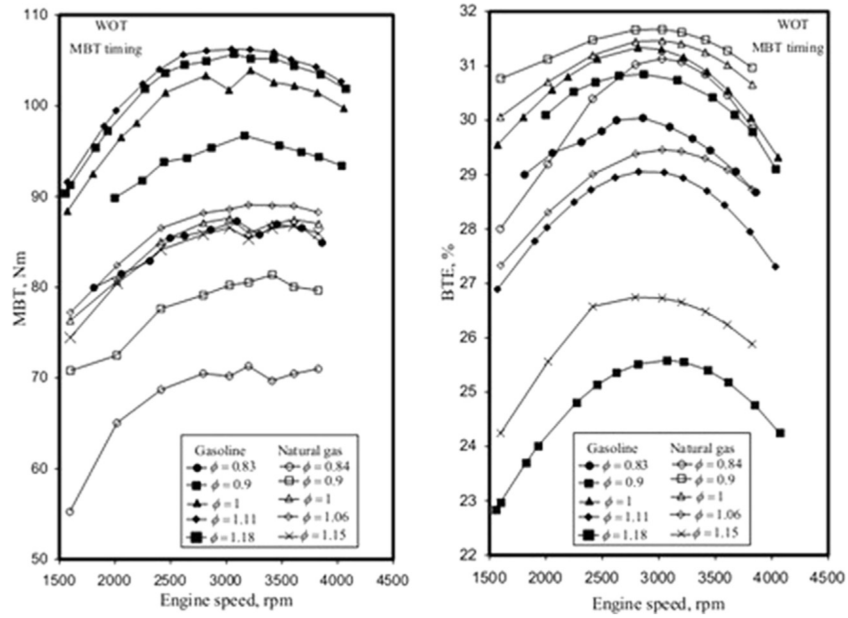


Fig. 15. MBT and BTE values versus engine speed at different equivalence ratios [47].

5. Natural gas in compression-ignition engines

5.1. Dual fuel CI operation

The earliest researches on utilization of natural gas in dual fuel engine in Iran were carried out at the end of 1980s. However, the main researches were done since the beginning of 2000s, as listed in Table 4.

Pirouzpanah and Asadi [50] used a model to predict Dual-Fuel Diesel Engine (D.F.D.E) performance, based on limited-pressure diesel cycle. The model predicts D.F.D.E performance with LPG, and CNG gases. By increasing gas proportion in dual-fuel mode, indicated power and hence indicated mean effective pressure were increased. Effect on thermal efficiency was not so significant, but indicated specific fuel consumption was quite considerable, and hence fuel economy of D.F.D.E was superior.

Pirouzpanah and Kashani [51] implemented a multi-zone combustion model (MZCM) to simulate D.F.D.E for diesel pilot jet combustion and a conventional S.I. combustion to model combustion of premixed gas/air charge. They also used four submodels to predict major emissions such as: UHC, NO, CO and soot emitted from D.F.D.E. Relevant conventional kinetically-controlled mechanisms and mass balances were used for prediction of formation and oxidation rates of pollutants. They verified the numerical results by experimental data obtained from a heavy-duty truck and bus diesel engines. The comparison showed that, there exists a good agreement between the experimental and predicted results from the D.F.D.E.

Sallamie et al. [52] utilized a monolithic oxidizing catalytic converter in a selected dual fuel (diesel/natural gas) engine for producing minimum NO_x and other possible emissions in order to meet the new environmental standards. They found that the tested catalytic converter reduces CO emissions about 100% while converting the other total hydrocarbons.

Based on the experimental results obtained by Pirouzpanah and Khoshbakhti Saray [53] the application of cooled EGR in a direct injection diesel engine dual-fueled with natural gas at higher loads with 10% EGR and at part loads with 15% EGR, can considerably reduce NO_x and other exhaust emissions such as unburned hydrocarbons, CO and soot. Results showed that the performance parameters almost remain at the baseline engine level. They pursued their investigation in [54] and carried out experiments to study combustion characteristics of a dual fuel (diesel–gas) engine at part loads, using a quasi-dimensional multi-zone combustion model (MZCM) for the combustion of diesel fuel and a single zone model with detailed chemical kinetics for the combustion of natural gas fuel. Their results demonstrated that increasing pilot quantity can provide better combustion process and also reduce NO_x emissions. In addition, air throttling can promote better combustion due to increasing total equivalence ratio and preparing better fuel air mixture for combustion. Also air throttling may increase NO_x emission despite its better effects on the dual fuel engine performance parameters.

Pirouzpanah and Khoshbakhti Saray [55] made further investigations to study the combustion characteristics of a dual-fuel (diesel–gas) engine at part loads with EGR, using a single-zone combustion model with detailed chemical kinetics for combustion of natural gas fuel. They indicated that a quasi-two-zone combustion model has ability to predict the combustion process with time and the associated important operating parameters, such as pressure, temperature, heat release rate (HRR), and species concentration. It was found that lower percentages of EGR have a positive influence on performance and emission parameters of dual-fuel engines at part loads. Pirouzpanah and Khoshbakhti Saray also [56,57] expounded the comparisons on the combustion and the emissions characteristics of dual fuel (diesel–gas) engines at part loads using EGR. They found that each of the different aspects of EGR including thermal, chemical and radical has a significant effect on the combustion process in dual fuel engines at part loads. It was found that all the aforementioned aspects of EGR have positive effects on the performance and emission characteristics of dual fuel engines at part loads despite the negative effect of some diluent gases in the chemical case, which moderates too much the positive effects of the thermal and radical cases of EGR (Fig. 17). They also made experimental investigations to study the emissions and performance characteristics of a dual fuel engine being operated on natural gas with pilot diesel injection. They introduced different levels of hot and cooled EGR into the engine in order to study its effect on combustion process, performance and emissions of dual fuel engines at part loads. The obtained results indicated that by employing hot EGR, the amount of EGR required to overcome the problems of dual fuel engines at part

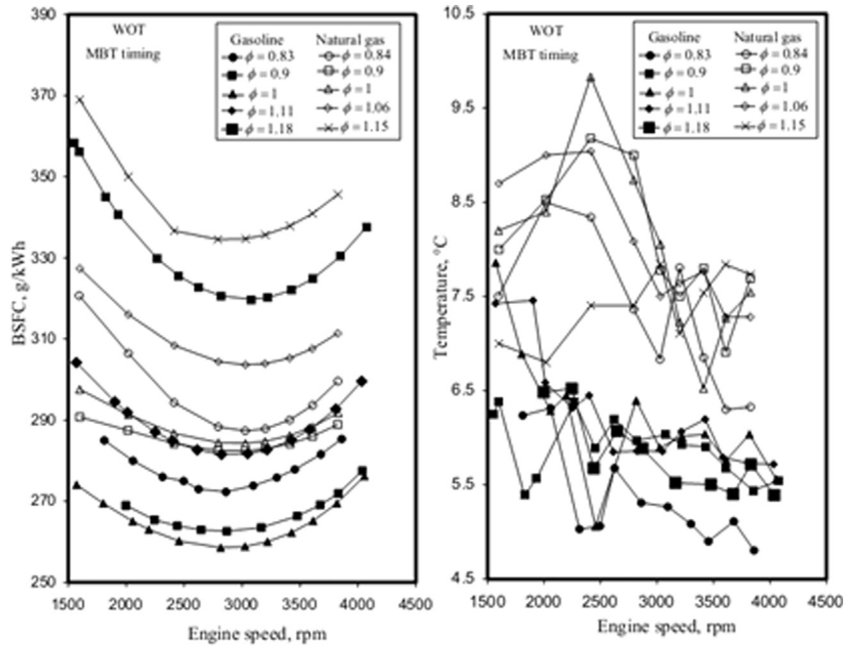


Fig. 16. BSFC and variation of water temperature difference between outlet and inlet engine values versus engine speed at different equivalence ratios [47].

load conditions is very low. It can be observed that, by employing high percentage of EGR at a constant temperature in comparison with low percentage of EGR, combustion process, performance and emission parameters deteriorate. In addition, low percentage of hot EGR at a critical temperature level reduces unburned hydrocarbons as well as carbon monoxide emissions sufficiently but increase in NO_x due to employing hot EGR is not remarkable. By employing low percentage of EGR in comparison with high percentage of EGR at a constant temperature, thermal and radical effects of EGR may overcome its dilution effects and vice versa. Fig. 18 demonstrates the variation of cylinder pressure, net heat release rate, UHC, CO and NO_x emissions with crank position for constant intake mixture temperatures and different percentages of EGR [58].

Hosseinzadeh et al. [59] developed a quasi-two-zone combustion model for studying the second-law analysis of a dual-fuel (diesel–gas) engine operating under part-load conditions using EGR. The model was consisted of a single-zone combustion model with chemical kinetics for combustion of natural gas fuel and a subsidiary zone for combustion of pilot fuel. The various availability components were identified and calculated separately with crank position. Then the different cases of EGR (chemical, radical and thermal cases) were applied to the availability analysis in dual-fuel engines at part loads. They found that the chemical case of EGR had negative effect and in this case the unburned chemical availability was increased and the work availability decreases in comparison with baseline engine (without EGR). While the thermal and radical cases had positive effects on the availability terms especially on the unburned chemical availability and work availability. The results indicated that second-law efficiency was increased by using low amount of radical and thermal cases of EGR.

Ghasemi and Djavareshkian [60] simulated combustion process, pollutants formation and flow field in combustion chamber of a DI Diesel engine converted to work as a dual fuel (diesel/natural gas) engine. The effects of natural gas equivalence ratio at constant Diesel pilot injection along with piston bowl shape were studied in different cases. The results showed that increasing natural gas has led to retarded and increased peak pressure which consequently results in an increase in NO_x level. In addition, higher swirl flow and more available oxygen led to more NO_x formation. Moreover, amount of soot was also increased.

Jafarmadar and Zehni [61] studied the effect of cold EGR on combustion and pollutant formation of a dual fuel (Diesel/natural gas) engine using the CFD code AVL FIRE and indicated that 10% EGR can reduce NO_x and Soot emissions significantly in comparison with the other cases. Of course, in the 15% EGR case, the emissions were the highest. Moreover, the NO_x emission was mainly formed close to the bowl of the piston and Soot emission is concentrated to the top of the piston bowl space.

Gharehghani et al. [62] numerically and experimentally conducted a detailed analysis of performance and combustion characteristic of a heavy duty diesel engine in dual fuel mode of operation where natural gas was used as the main fuel and diesel oil as pilot. They expounded the effects of intake pressure and temperature on knock occurrence and the effects of initial swirl ratio on heat release rate, temperature-pressure and emission levels. They found that increasing initial intake swirl ratio in dual fuel engines can reduce NO_x emissions, the maximum and minimum cylinder pressure and temperature, and the possibility of knock, while increasing heat loss. The amount of power loss in dual mode of operation was reduced while increasing intake temperature and pressure; however, this increase may lead to initiation of knock and engine damage. They found that simultaneous increase of intake pressure and initial swirl ratio could be the best solution; overcoming the power loss in dual fuel engine at the same time and prevention of knock occurrence.

Paykani et al. [63] investigated the simultaneous effect of EGR and pre-heating of the inlet air on performance and emission characteristics of dual fuel (diesel/natural gas) engines at part loads. They showed that constant EGR percentages combined with variation of intake mixture temperature can favorably increase brake thermal efficiency; however, it can be observed that, by employing high percentage of EGR at a constant temperature thermal efficiency deteriorates. Besides, constant intake mixture temperatures combined with variation of EGR percentage resulted in good reductions in thermal efficiency and engine emissions. EGR combined with pre-heating of inlet air reduces NO_x, UHC and CO emissions without deteriorating engine thermal efficiency.

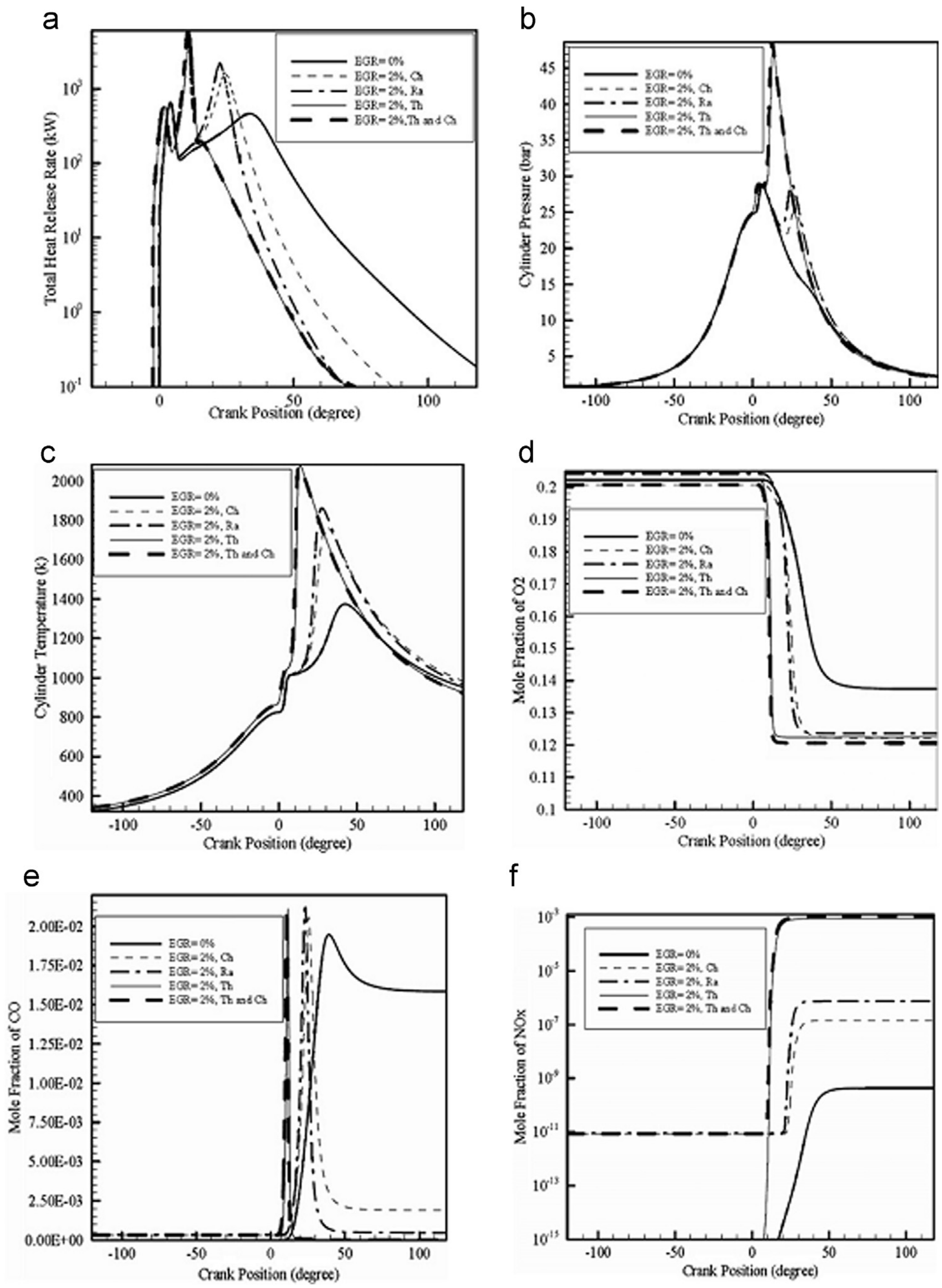


Fig. 17. (a) total heat release rate; (b) cylinder pressure; (c) cylinder temperature; (d) mole fraction of O_2; (e) mole fraction of CO; (f) mole fraction of NO_x [56].

5.2. HCCI operation

A homogeneous charge compression ignition (HCCI) combustion engine has been known, in which air-fuel mixture gas including air and fuel is formed in a combustion chamber and the air-fuel mixture is self-ignited to be burned by compressing the air-fuel mixture during a compression stroke. HCCI is a good method for higher efficiency and to reduce NO_x and particulate matter simultaneously in comparison to conventional internal combustion engines [64]. Although HCCI combustion has recently attracted the Iranian researchers, numerous research works have been published in national and international journals and conferences during last 5 years (Table 5).

Rahbari [65] employed a mechanism containing ethanol reactions and studied effects of EGR on operation parameters such as ignition timing, burn duration, temperature, pressure and NO_x emissions. He reported that the increase of EGR delays the ignition timing, slows down the combustion reaction rate, reduces the temperature and pressure in cylinder, and decreases the NO_x emissions. Furthermore, he calculated heat transfer from cylinder contents to surrounding surfaces using Woschni's heat transfer correlation.

Noorpoor et al. [66] investigated the effect of additives such as hydrogen (H_2), hydrogen peroxide (H_2O_2), formaldehyde (CH_2O) and ethane (C_2H_6) on the control of ignition in natural gas HCCI engines. The SENKIN code was used to simulate the in-cylinder chemical reactions. They found that an additive free mixture was not ignited the mixture at an intake temperature of 500 K while a mixture containing a small quantity of additives at the same temperature was able to initiate chemical reaction. For a fixed quantity of additive, it was found that H_2 addition was effective in advancing the ignition timing as is compared with the other three

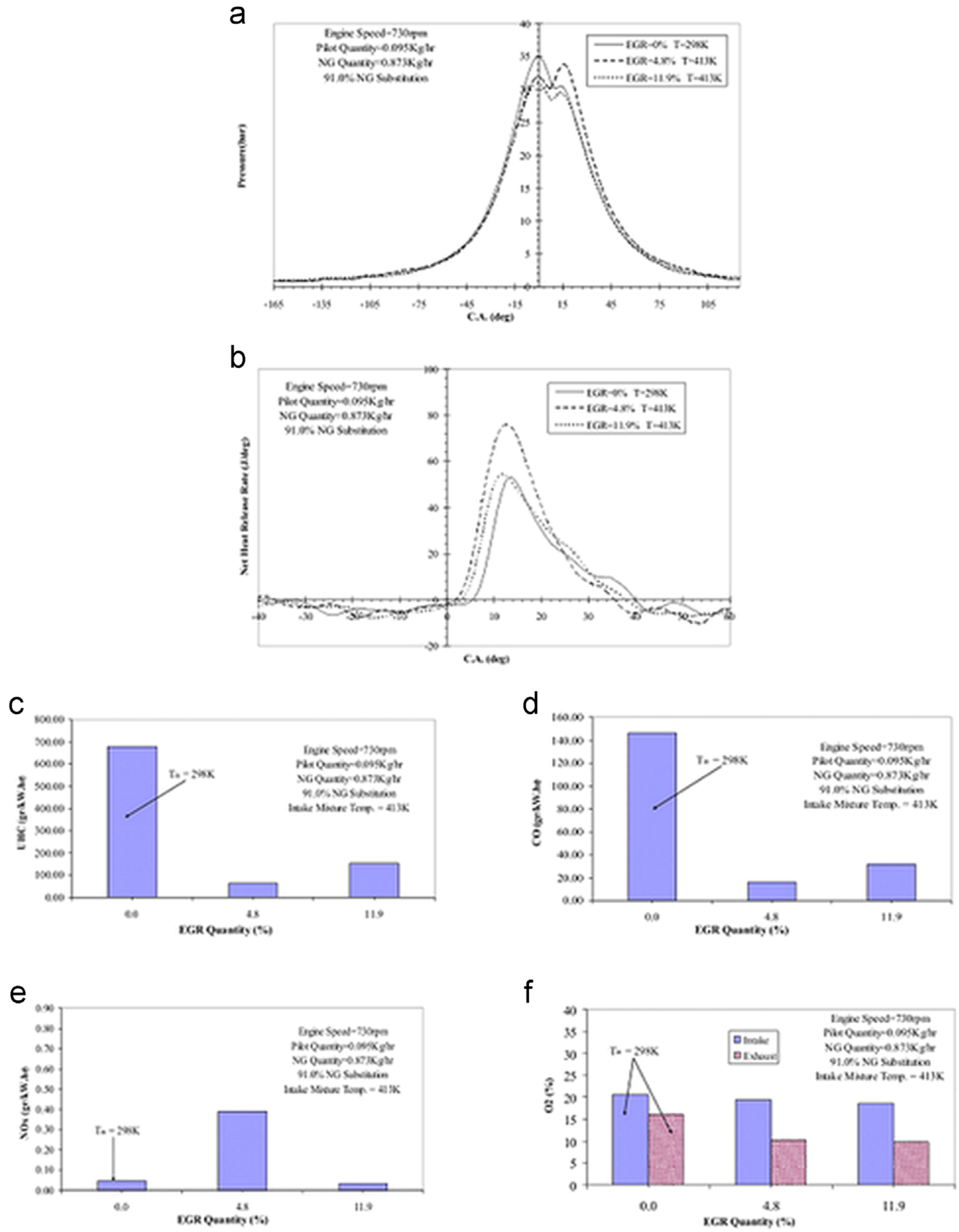


Fig. 18. Variations of: (a) cylinder pressure; (b) net heat release rate; (c) UHC; (d) CO; (e) NO_x; (f) O_2 with crank position for constant intake mixture temperatures and different percentages of EGR [58].

additives. In addition, the engine peak pressure has been moved to the location before top dead center. Moreover, the percentage of additives required in achieving near TDC ignition, increases linearly with an increase in engine speed. A small addition of H_2O_2 ignites the mixture at an intake temperature of 450 K.

Rahimi et al. [67] optimized the chemical kinetic mechanisms available for *n*-heptane and natural gas to be used in a binary-fuel blend scenario. A combined mechanism was optimized using the genetic algorithm method and the modeling results were verified against experimental ones. They used a fuel blend of *n*-heptane (diesel-like fuel) and natural gas was one of the best available options because dual-fuel diesel–natural-gas engines have already been used.

Nobakht et al. [68] presented a modeling study of a CNG Homogenous Charge Compression Ignition (HCCI) engine using a single-zone and a multi-zone combustion model. They developed a code to predict engine combustion and performance parameters in closed part of the engine cycle. In order to investigate chemically kinetics of combustion process in HCCI engines in detail, GRI-mech 3.0 combustion mechanism was developed for natural gas combustion without considering EGR. The predicted values showed good agreement with corresponding experimental ones for whole ranges of engine operating conditions. They conducted another research work dealing a parametric study on natural gas HCCI combustion in order to identify the effect of inlet temperature and pressure, compression ratio, equivalence ratio and engine speed on combustion and engine performance characteristics. A six zone model coupled with detailed chemical kinetics code was used to simulate HCCI combustion. Results revealed that the equivalence ratio and inlet pressure are the most valuable parameters which can improve the combustion and performance characteristics of the HCCI engine (Fig. 19) [69].

Fathi et al. [70] firstly studied traditional first law heat release model widely used in engine combustion analysis and the

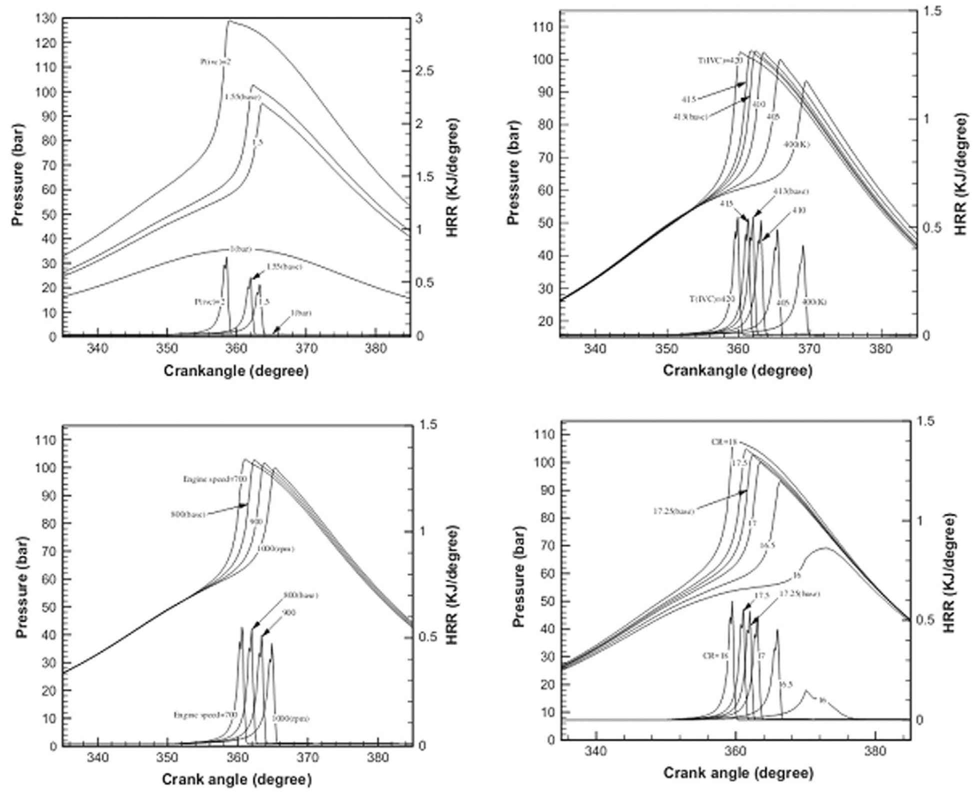


Fig. 19. Effect of: (a) inlet pressure variation; (b) inlet temperature variation; (c) engine speed; (d) compression ratio on pressure and HRR histories [69].

applicability of this model in HCCI engines. Second, a new heat release model based on the first law of thermodynamics accompanying with a temperature solver was developed and assessed. Four test conditions and a variety of fuel compositions, including *i*-octane, *n*-heptane, pure NG, and at last, a dual fueled case of NG and *n*-heptane were used. Results indicated that utilizing the modified first law heat release model together with a solver for temperature correction will guarantee obtaining a well-behaved and accurate apparent heat release trend and magnitude in HCCI combustion engines. They also carried out experiments in order to investigate the possibility of controlling combustion phasing and combustion duration using various EGR ratios. A modified apparent heat release model was developed. The influence of EGR on emissions was discussed. Results represented that applying EGR reduces mean charge temperature and has profound effect on combustion phasing, leading to a retarded start of combustion (SOC) and prolonged burn duration. In addition, EGR addition improved fuel economy, reduced NO_x emissions and increased HC and CO emissions in specific conditions [71].

They further investigated the HCCI combustion fueled by natural gas and *n*-heptane in a Waukesha CFR single cylinder research engine with variable EGR. The primary objective of their experiments was to make an attempt to control the combustion timing and duration by studying different approaches such as varying EGR rates, intake charge temperature and compression ratio. They employed a modified first law apparent heat release model developed by the authors. Their results indicated that applying EGR has a profound effect on combustion phasing, leading to a retarded SOC and prolonged burn duration. Moreover, the influence on emission characteristics was desirable regarding NO_x formation and unfavorable in the case of CO and HC emissions in a dual fueled HCCI combustion engine [72].

Amjad et al. [73] investigated the exergy analysis of HCCI combustion when a blended fuel (*n*-heptane and natural gas) is used. A single-zone combustion model has been developed, performing combustion computations using a complete chemical kinetics mechanism. The study was carried out with different percentages of natural gas in blended fuels and EGR ratios ranging from about 45 to 85% and 0 to 40%, respectively. Their results revealed that, when percentage of natural gas increased, exergy destruction was decreased increasing the second-law efficiency. Introducing EGR in to the intake charge of dual fuel HCCI engine up to some stage enhances the second-law performance of the engine in spite of a reduction in work.

Jahanian and Jazayeri [74] studied the performance of a natural gas HCCI engine through a thermodynamic model including detailed chemical kinetics. It was shown that as hydroxyl radical had great influence on natural gas combustion, it was possible to quantify SOC with hydroxyl concentration variations. Meanwhile the effect of using formaldehyde as an additive on the engine characteristics has been investigated. Results showed that it was possible to change the engine working limits using this additive. Lower auto-ignition temperature of formaldehyde causes advanced combustion in natural gas HCCI engine. It was also shown that the air/fuel mixture will ignite earlier using this additive so it is conceivable to reduce inlet mixture temperature resulting in better performance due to higher volumetric efficiency. They further investigated the influence of natural gas composition on engine operation in HCCI mode. Six different compositions of natural gas have been considered to study the engine performance via a thermo-kinetic zero-dimensional model. The simulation code covered the detailed chemical kinetics of natural gas combustion, which includes Zeldovich extended mechanism to evaluate NO_x emission. Results indicated that the peak value of pressure/temperature of in-cylinder mixture is dependent of fuel Wobbe number. Furthermore, engine gross indicated power was linearly related to fuel Wobbe number. Gross indicated work, gross mean effective pressure, and NO_x were the other parameters utilized to compare the performance of engine using different fuel compositions [75].

Table 3
Progress and main research works on natural gas fueled spark ignition engines.

Researchers (time)	Experimental equipment or numerical approaches	Research objects
Dordaei et al. [34] Shariat [35]	4 cylinder, four stroke, 82 mm bore, 88 mm stroke, 1.8 L displacement, CR = 10.1 4 cylinder, four stroke, 78 mm bore, 84 mm stroke, 1.8 L displacement, CR = 9.6	air-fuel ratio, the shape of combustion chamber and spark timing on pollutant emissions Power and emissions characteristics
Shamekhi et al. [12,36]	4 cylinder, four stroke, 86 mm bore, 86 mm stroke, 1.99 L displacement, CR = 8.6	Volumetric efficiency, thermal efficiency, HC, NO_x, CO and CO_2 emissions
Andalibi and Ahmadi [37]	4 cylinder, four stroke, 87.3 mm bore, 66.7 mm stroke, 1.6 L displacement, CR = 7.8	amount of charged air, torque and power
Ghanbari et al. [38]	Numerical research by FORTRAN code	Thermal efficiency, engine knock, effect of EGR
Dashti et al. [39,40]	As the above	Power, IMEP, ISFC, thermal efficiency, equivalence ratio, compression ratio, spark timing emissions concentration
Abianeh et al. [41]	4 cylinder, four stroke, 78 mm bore, 72 mm stroke, 1.37 L displacement, CR = 10.8	Wall temperature, performance and emissions
Mirsalim et al. [42]	4 cylinder, four stroke, 78.6 mm bore, 85 mm stroke, 2 L displacement, CR = 9.9	Engine efficiency, energy and exergy
Firouzgan [43]	4 cylinder, four stroke, 87.3 mm bore, 66.7 mm stroke, 1.6 L displacement, CR = 7.8	Performance, emissions and fuel consumption
Rezapour et al. [44,45]	4 cylinder, four stroke, 83 mm bore, 81.4 mm stroke, 1.76 L displacement, CR = 9.25	Volumetric efficiency, brake power, brake mean effective pressure, torque, brake specific fuel consumption and emissions
Behnam et al. [46]	4 cylinder, four stroke, 87 mm bore, 90 mm stroke, 2.15 L displacement, CR = 11.1	Brake power, brake torque, brake mean effective pressure and brake specific fuel consumption
Ebrahimi and Mercier [47,48]	4 cylinder, four stroke, 76 mm bore, 87 mm stroke, 1.8 L displacement, CR = 9.6	Spark timing, equivalence ratio, exhaust gas temperature and BSFC
Asgari et al. [49]	4 cylinder, four stroke, 85 mm bore, 78.6 mm stroke, 2 L displacement, CR = 11	NO_x emissions

6. Summary and conclusions

From the above review, it can be concluded that natural gas is a domestic, abundant and promising alternative fuel for SI and CI engines in Iran. Iran is one of the most polluted countries and it has the world's first largest reserves of natural gas. Thus, it can be widely used in transport section in attractive prices. Iran has the world largest NGV fleet with 3.30 million vehicles and it is one of world's fast growing countries in terms of the highest number of CNG stations.

The present review reports that the research on natural gas fueled engines in Iran can sorted into two kinds: research on SI and CI natural gas fueled engines. The former kind engines are aiming at making improvements on both energy saving and emissions reduction in vehicles, and the later kind engines are aiming at developing a novel high-efficiency and low-emissions vehicles for the future Iranian vehicle industry. The amounts of achievements obtained by the Iranian researchers and technologies on the later kind engines are relative mature in Iran. Their most achievements include the detailed mechanism of the combustion and emissions characteristics of dual-fuel, and HCCI engines. They promoted the application of natural gas in the vehicles in Iran and can accelerate further research works on natural gas fueled vehicles in Iran. Albeit the research on the later kind engines had begun since the beginning of the 2000s, the shortage of natural gas refueling infrastructures, experimental facilities and the knowledge on the combustion characteristics of natural gas limited the development of NGVs, but most of the obstacles have been solved in the current Iran, since natural gas refueling stations and other natural gas infrastructure have been established successfully in different parts of Iran.

It was also found that conversion of conventional SI and CI engines to run on natural gas is a promising solution to reduce pollutant emissions. Natural-gas fueled SI engines can operate at higher compression ratios resulting in similar or slightly higher thermal efficiencies producing lower pollutant emissions compared to gasoline-fueled engines. The higher hydrogen-to-carbon ratio of natural gas results in slight reductions of CO_2 emissions compared to gasoline engines. High compression ratios and advanced spark timing are implemented which generally increases NO_x emissions along with reductions in HC and CO emissions. EGR has been also used to reduce NO_x emissions but it results in an increasing of HC and CO emissions. Performance and emission characteristics of SI natural gas-fueled engines have been investigated by Iranian researchers. Different parameters such as spark timing, valve timing, air-fuel ratio and EGR have been taken into account to improve the operation of engine.

Dual fuel operation with natural gas fuel can yield a high thermal efficiency almost comparable to the same engine operating on diesel fuel at higher loads. However, engine performance and emissions suffer at low loads when operating in dual fuel mode. In most of the literature the part load operation of dual fuel engines was investigated by Iranian researchers. Different techniques such as introduction of hot and cold EGR, pilot injection timing and inlet air temperature have been studied and it was shown that effects of combined EGR and pre-heating of inlet air reduces NO_x, UHC and CO emissions without deteriorating engine thermal efficiency.

The major problem associated with HCCI engines, is no direct control method for auto-ignition time. Generally, the ignition timing in HCCI engines can be indirectly controlled by varying engine's parameters which can influence the combustion. Different techniques such as effects of additives, inlet temperature and pressure, compression ratio, equivalence ratio, engine speed and EGR have been investigated and the results indicated that the equivalence ratio and inlet pressure are the most valuable parameters which can improve the combustion and performance characteristics of the HCCI engine. Furthermore, EGR decreases peak cylinder pressure and pressure rise rate during combustion and is a promised means of enhancing HCCI combustion.

In the future, numerous research works and achievements on natural gas fueled engines must be presented to the world from Iran such as the effects of EGR or water (to reduce NO_x) or hydrogen (to accelerate combustion progress) on combustion and emission characteristics of these engines. It is not well known how combinations of different performance parameters such as

Table 4
Progress and main works on the researches of natural gas application in dual fuel engine.

Researchers (time)	Experimental equipment or numerical approaches	Research objects
Pirouzpanah and Asadi [50]	OM-355 Diesel–Natural, 6 cylinders, four stroke, 128 mm bore, 150 mm stroke, 11.58 L displacement, CR = 16.1	thermal efficiency, indicated specific fuel consumption
Pirouzpanah and Kashani [51]	As the above	Combustion and UHC, NO, CO and soot emissions
Sallamie et al. [52]	4 cylinders, four stroke, 105 mm bore, 105 mm stroke, 3.6 L displacement, CR = 17.5	NO_x and other possible emissions
Pirouzpanah and Khoshbakhti Saray [53–55]	Numerical research by FORTRAN and comparison with OM-355 experiments	Performance and emissions characteristics at various EGR ratios, pressure, temperature, heat release rate (HRR), and species concentration
Pirouzpanah et al. [56]	As the above	Effect of EGR on the combustion process in dual fuel engines at part loads
Khoshbakhti Saray et al. [57,58]	Single cylinder, four stroke, Lister (8-1) IDI, 114.1 mm bore, 139.7 mm stroke, 1.43 L displacement, CR = 17.5	Performance and emissions characteristics at various hot and cooled EGR ratios at part load conditions
Hosseinzadeh et al. [59]	Numerical research by FORTRAN	Effect of EGR on availability analysis in dual-fuel engines at part loads
Ghasemi and Djavareshkian [60]	Numerical research by AVL FIRE	combustion process, swirl flow, NO_x and soot formation
Jafarmadar and Zehni [61]	As the above	Cold EGR on NO_x and Soot emissions
Gharehghani et al. [62]	Numerical research by KIVA-3V	Knock, initial swirl ratio, heat release rate, temperature-pressure and emission levels
Paykani et al. [63]	Single cylinder, four stroke, Lister (8-1) IDI, 114.1 mm bore, 139.7 mm stroke, 1.43 L displacement, CR = 17.5	High EGR percentages combined with variation of intake mixture temperature, performance and emissions characteristics

Table 5
Progress and main works on the researches of natural gas application in HCCI engine.

Researchers (time)	Experimental equipment or numerical approaches	Research objects
Noorpoor et al. [66]	Numerical research by SENKIN and GT-Power	Effect of additives, control of ignition
Rahimi et al. [67]	Numerical research by FORTRAN code	Optimization of chemical kinetic mechanisms, *n*-heptane and natural gas, detailed chemical kinetics
Nobakht et al. [69]	Numerical research by FORTRAN and comparison with Waukesha CFR, 82.6 mm bore, 114.3 mm stroke, 0.612 L displacement, CR = 16	Effect of inlet temperature and pressure, compression ratio, equivalence ratio, engine speed and EGR on combustion and engine performance parameters.
Fathi et al. [70–72]	As the above	Obtaining new heat release model, controlling combustion phasing and combustion duration using various EGR ratios
Amjad et al. [73]	As the above	Exergy analysis, different percentages of natural gas in blended fuels and EGR
Jahanian and Jazayeri [74,75]	Numerical research by MATLAB and comparison with Caterpillar 3500, 170 mm bore, 190 mm stroke, 2.6 L displacement, CR = 17	Thermodynamic model, detailed chemical kinetics, effect of additives on the engine characteristics, influence of Natural Gas composition on engine operation and NO_x Emissions

compression ratio, equivalence ratio, ignition timing for SI engines or fuel-injection timing for dual-fueled CI engines affect the exhaust emissions of natural gas engines. Additional research is needed to optimize dual-fuel CI-engine operation with natural gas. Studies to vary pilot fuel amounts at different engine loads and to vary injection timing and pressure are required in order to optimize emissions characteristics. Moreover, effects of natural gas composition on the performance and emissions of natural gas fueled engines would be one of interesting topics for Iranian researchers.

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